CTSRD

CRASH-worthy Trustworthy Systems Research and Development

CTSRD Project Briefing

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CTSRD at the PI Meeting


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Dr Simon W. Moore


Dr Jonathan Anderson


Dr David Chisnall


Dr Nirav Dave


Mr Brooks Davis


Mr Rance DeLong


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Mr Ed Maste


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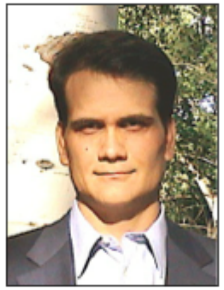
Mr Colin Rothwell


Mr Stacey Son

CTSRD

- Spans security, CPUs, OS, compilers, languages, program analysis/transformation, HW/SW formal methods.
- Clean-slate design violates some current conventions, in exchange for dramatic security improvements.
- Capability-based CPU protection and compartmentalization features mitigate known and unknown vulnerability classes.
- Hybrid model facilitates incremental SW adoption.
- Program analysis and transformation techniques improve software TCB correctness, utilize new CPU features.
- Formal methods link models, hardware, and software.

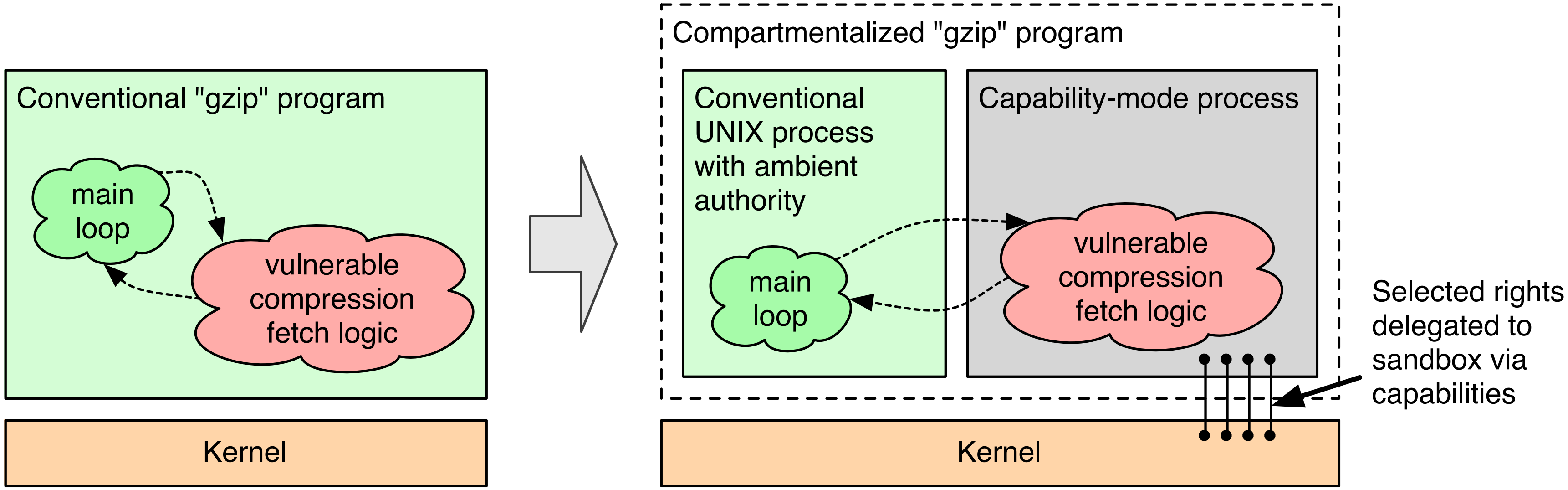
CTSRD project elements

- Capsicum, compartmentalization, and CTSRD
- Capability Hardware Enhanced RISC Instructions (CHERI)
  - CHERI ISA and hardware compartmentalization prototype
  - CHERI platform: tablet, CheriCloud, peripherals, etc.
  - CHERI software: CheriBSD, CHERI Clang/LLVM, apps
  - Architectural extraction, verification of Bluespec (Smten)
  - ISA-level proofs and automated test generation
- Security-Oriented Analysis of Application Programs (SOAAP)
- Temporally Enhanced Security Logic Assertions (TESLA)

August 2013 CTSRD/MRC2 meetings, Cambridge, UK

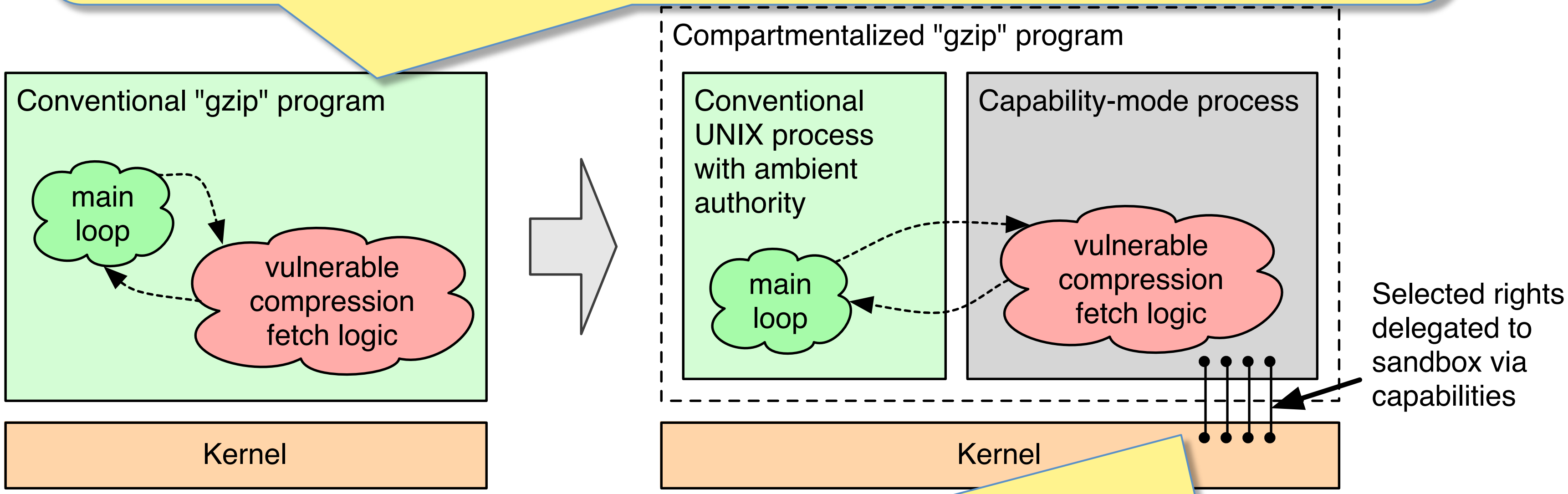
COMPARTMENTALIZATION FOUNDATIONS

Application compartmentalization



- Compartmentalization decomposes software into isolated components.
- Each sandbox runs with only the rights required to perform its function.
- This model implements the principle of least privilege.

When a conventional application is compromised, ambient rights are leaked to the attacker, e.g., network and file system access.

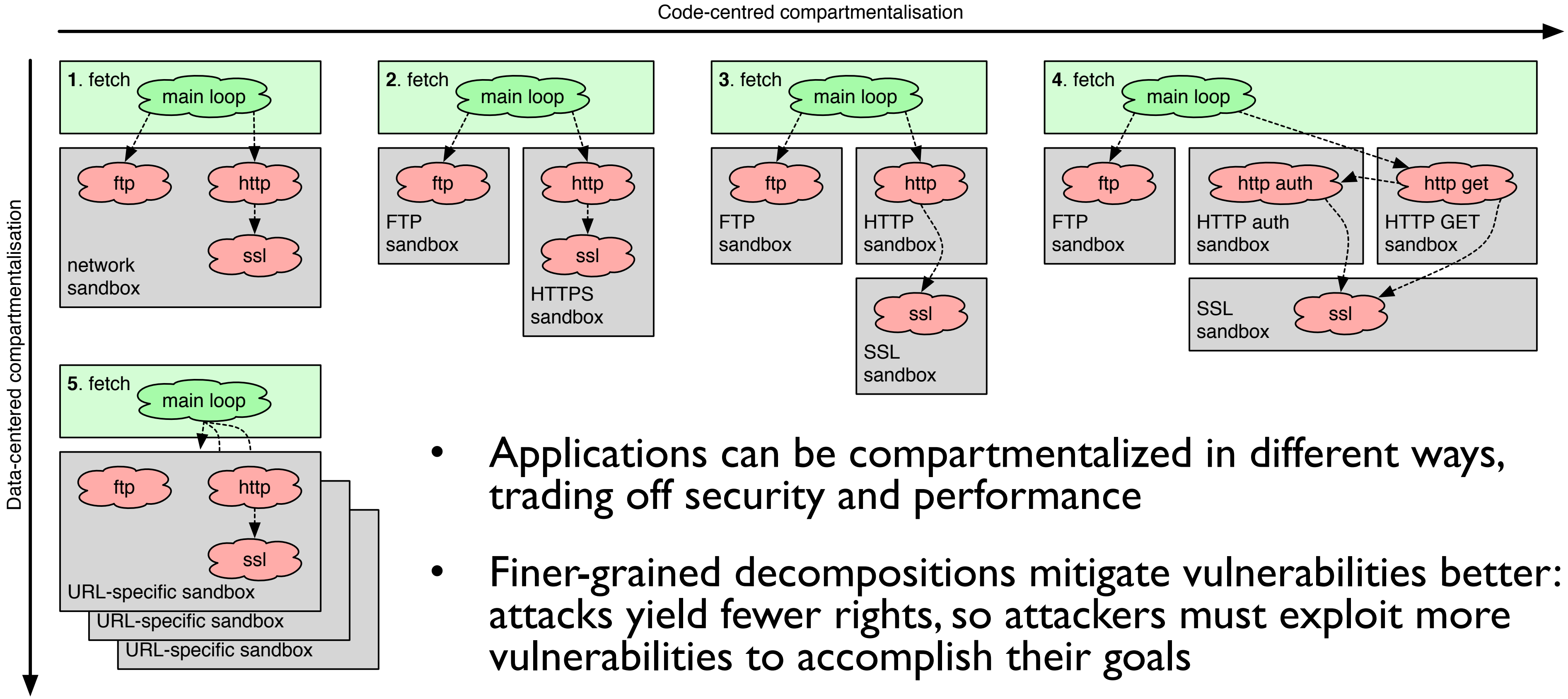


Compromising a compartmentalized application yields only held rights to the attacker.

As vulnerabilities yield fewer rights, attackers must exploit many vulnerabilities to meet their goals.

Capsicum update

- Hybrid capability model: OS APIs for application compartmentalization
- Joint Cambridge/Google project
- Experimental feature in FreeBSD 9.x; out-of-the box in 10.0 (RSN)
- FreeBSD Foundation, Google
  - Funded projects will continue in 2014
  - Growing number of FreeBSD programs are using Capsicum out-of-the-box: tcpdump, auditdistd, hastd, etc.
  - Casper framework offers services to sandboxes (e.g., DNS, socket server)
- Google has published a Linux port prototype and hopes to upstream

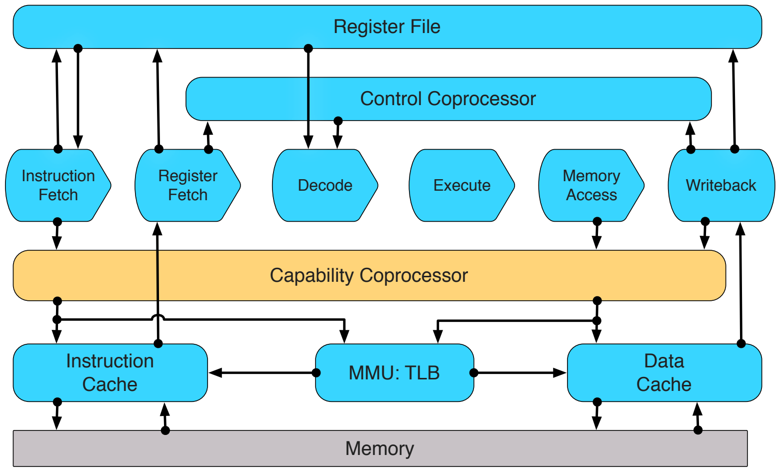


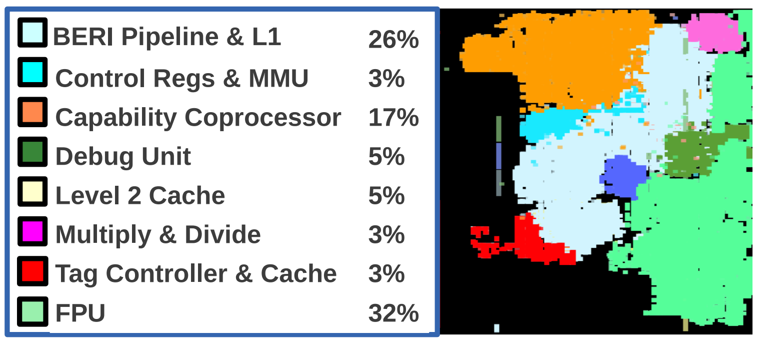
- Applications can be compartmentalized in different ways, trading off security and performance
- Finer-grained decompositions mitigate vulnerabilities better: attacks yield fewer rights, so attackers must exploit more vulnerabilities to accomplish their goals
- Ideally, web browsers would use hundreds/thousands of sandboxes: one for each image, script, etc.
- However, CPUs support few simultaneous processes; e.g., Google Chrome reuses up to 20 sandboxes, one per tab
- As a consequence of CPU design, malware in a webmail image attachment can access a user's entire mailbox

Capability hardware enhanced RISC instructions

CHERI PROCESSOR

Capability hardware enhanced RISC instructions (CHERI)

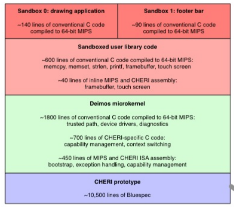




- CHERI hybrid capability model:
  - Fine-grained memory protection
  - In-address-space sandboxing
- Extends 64-bit MIPS ISA
- Haskell-derived Bluespec System Verilog HDL; synthesizes to Altera and Xilinx FPGAs
- Fully pipelined; multithreaded and multicore under development
- Extensive test suite and tools
- ISA and design subject to new formal analysis
- Shortly to be released as open source

CHERI development timeline

October 2011: Deimos capability-based microkernel runs first sandbox



June 2012: CheriBSD capability context for user threads

July 2012: LLVM generates CHERI ISA code

November 2012: Sandboxed user code runs on CheriBSD; trojan mitigated

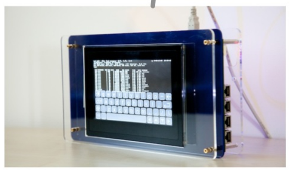
December 2012: Nested sandboxes and sandbox exception handling

Feburary 2013: CHERI box on the Internet

January 2014: CheriBSD now uses CHERI Clang/LLVM for key sandboxing components

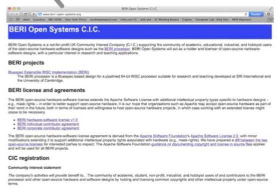
2010 — 2011 — 2012 — 2013 — 2014

November 2011: tPad tablet demo with Deimos



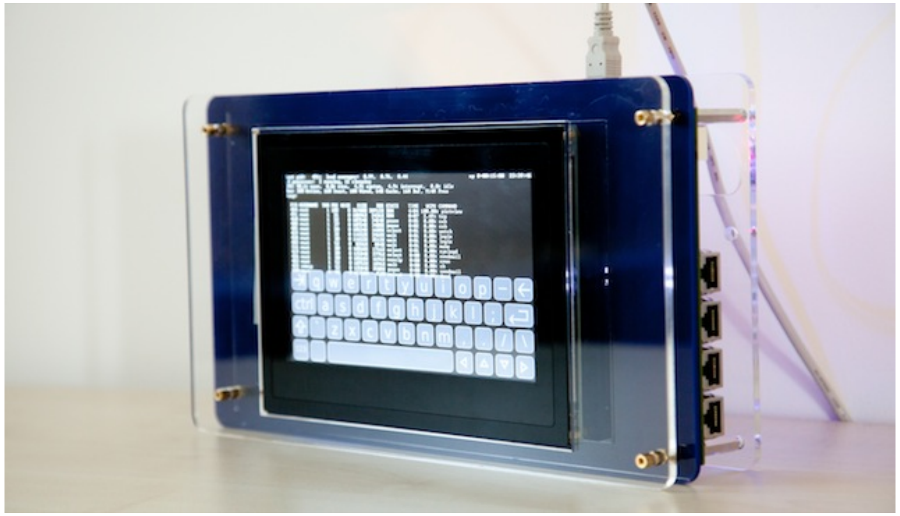
May 2012: DE4 tablet runs FreeBSD

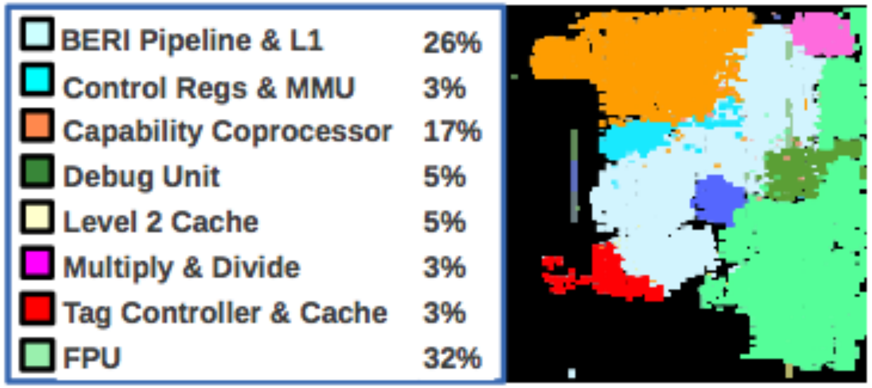
April 2013: CheriCloud online for SRI/Cam users



December 2013: BERI Open Systems CIC created

CHERI hardware platform





- CHERI prototypes
- Tablet prototype: CPU, DRAM, battery, flash, touchscreen, HDMI, Ethernet
- In-field CPU, OS updates
- CheriBSD OS, CHERI SDK
- CHERI demonstrations
  - E.g., fine-grained compartmentalization in CheriPoint presentation package

CheriCloud

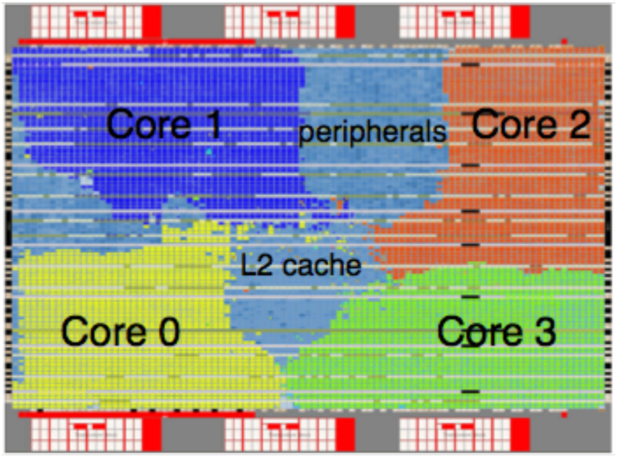
- Centralized facility supporting remote CHERI software development for CTSRD and MRC2 projects
- 7 x DE4 FPGA boards in 4U
- CHERI CPU + CheriBSD with Ethernet on each DE4
- Reset and serial console
- SSH into a live CHERI system; off-the-shelf open-source applications
- Total end-user transparency!

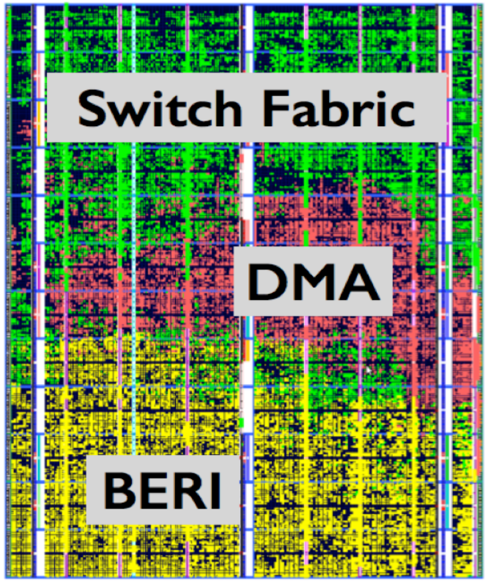
CHERI enhancements (CTSRD)

- CHERI ISAv2.1 enhancements to object-capability invocation, software debugging features
- FPU – particularly useful for Olden benchmarks
- Improved hardware ISA-level tracing + CheriVis
- CHERI2 now fully implements ISAv2.1
- Annabella release in July 2013
- Multithreaded CHERI2 boots BSD in simulation
- Multicore CHERI in testing

CHERI enhancements ($(MRC)^2$)

- DARPA MRC sister project also using and enhancing CHERI
- Multithreading and multicore
- Multi-FPGA interconnect
- AXI bus conversion
- NetFPGA 10G
- CPU Tracing enhancements
- FPU maturity
- BlueSwitch





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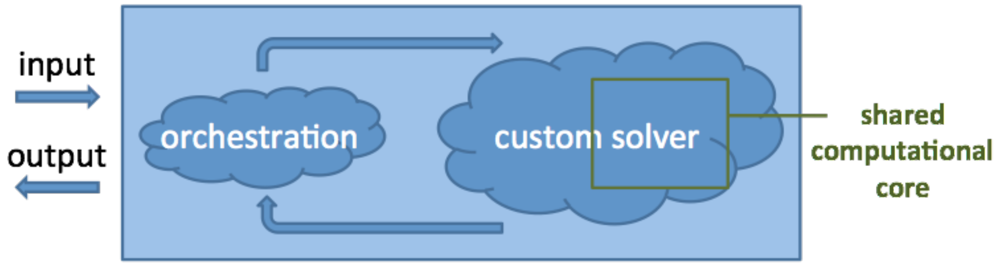
CHERI formal verification: ISA model

- Formal model of ISA described in SAL model checker
- Bluespec CHERI and CHERI2 capability units are automatically tested against the SAL model
- New: we can now automatically translate the SAL model into PVS
- Using PVS, we can prove "memory safety" for a CHERI ISA subset
- Future work: prove security properties of full model
- Future work: prove security properties of key software TCB elements (e.g., CCall, Creturn)

CHERI formal verification: Bluespec analysis / Smten

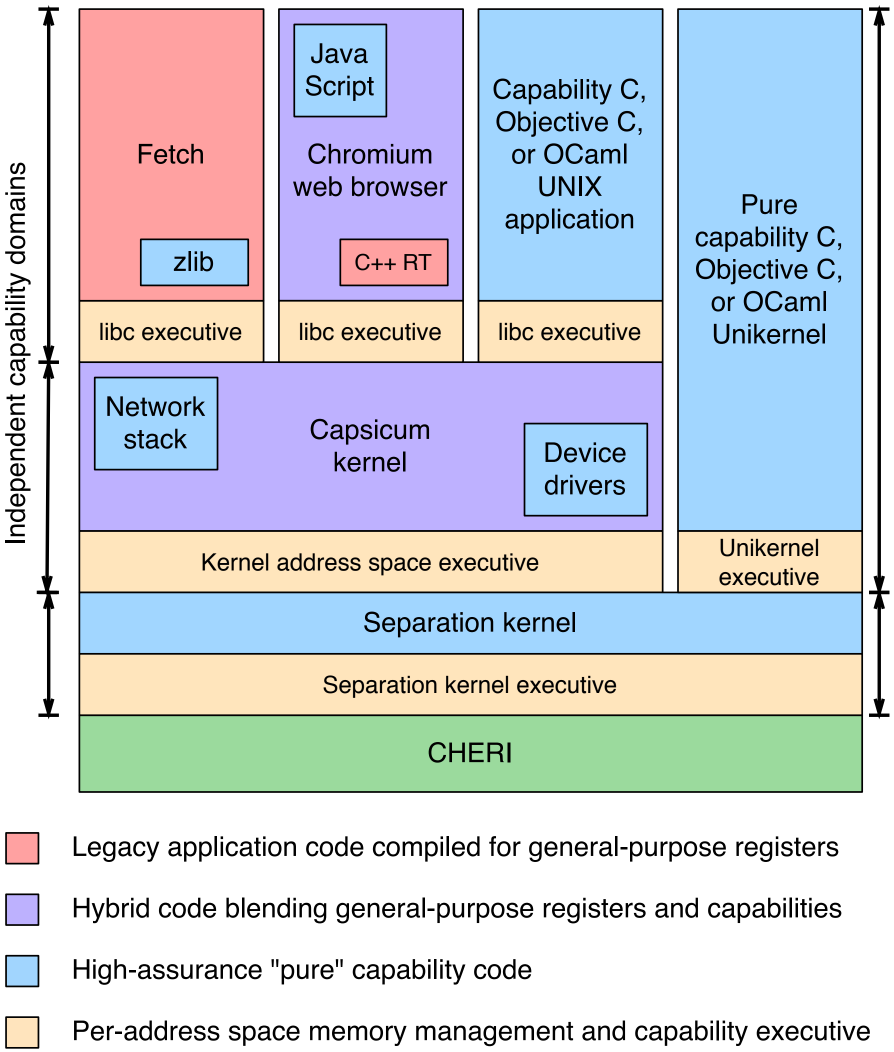
- Smten: Automatic Translation of High-level Symbolic Computations into SMT Queries
- Motivation: SMT solvers are widely used for model checking, automated theorem proving and test generation, but translating a model into an SMT form is tedious
- Solution: Smten is a high-level, purely functional language, with syntax and features borrowed heavily from Haskell which greatly helps translation of models into SMT queries
- Initial work published at CAV'13
- See Nirav Dave during the poster session for details.



Verification Tool – Before SMT

CHERI SOFTWARE

CHERI software model



- Fine-grained userspace memory protection, in-process sandboxing
- MIPS/CHERI binaries tightly integrated (e.g., CHERI library in MIPS binary)
- Compiler allows pointers to be replaced with tagged, bounds-checked capabilities
- In-progress CHERI debugger
- OS support for model, tracing tools, etc.
- Userspace sandbox model, class libraries, components, monitoring tools
- CheriBSD on github so more easily accessible to downstream users
- BERI support + drivers shipping as FreeBSD 10.0 embedded target in weeks

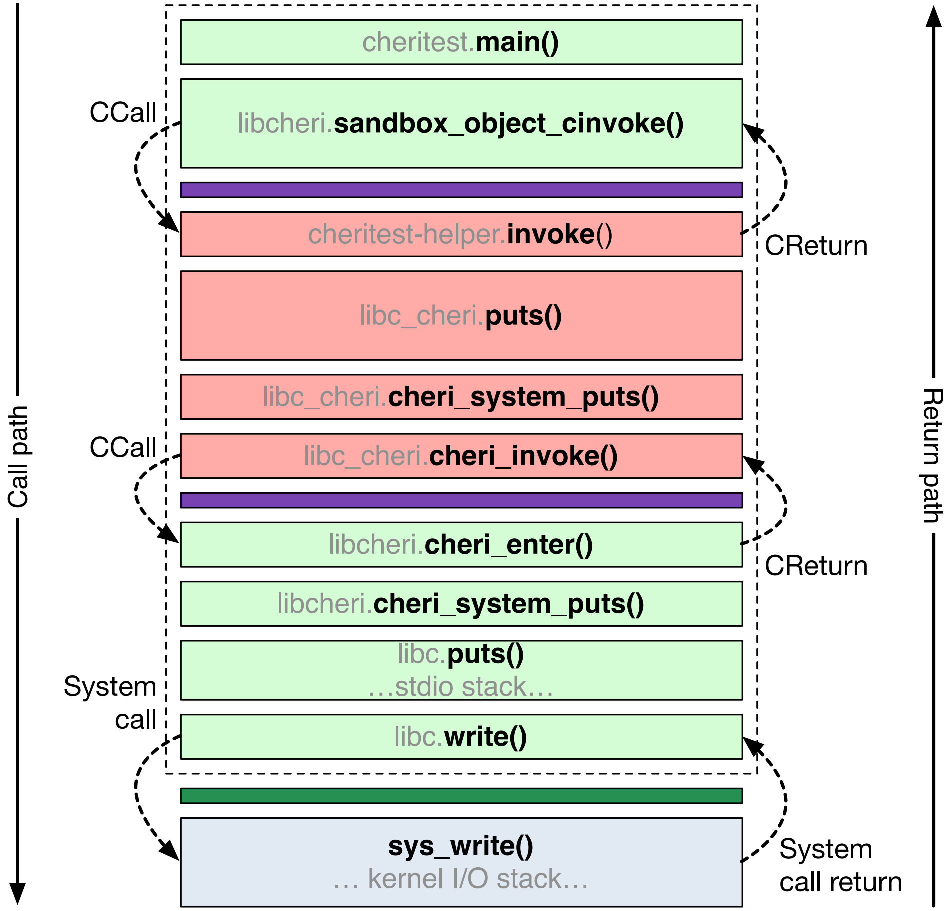
CHERI extensions to FreeBSD

- CHERI register file preserved for each user thread
- CCall/CReturn exception handlers: object-capability invocation
- CHERI "trusted stack" for object-capability return path
- Sandbox fault recovery unwinds trusted stack on MMU fault, capability fault, or other thread traps
- Kernel accepts system calls only from in-process protection domains with ambient authority; requires using the system class
- Kernel debugging extensions for CHERI LLDB
- CHERI memory protection via CHERI Clang/LLVM
- libcheri(3) API to create and invoke sandboxes
- Extensions to the procstat(1) tool to track sandbox state

CHERI Clang/LLVM/LLDB

- CHERI Clang/LLVM
  - Clang supports new qualifiers, builtins for capability manipulation
  - LLVM CHERI code generation extends MIPS support
  - Pointers use MIPS representation and instructions by default
  - Pointers tagged as __capability generates CHERI instead of MIPS
  - Experimental CCured work automatically converts C code to CHERI ISA
- CHERI SDK
  - Complete cross-development environment: toolchain, libraries, headers.
- CHERI LLDB
  - LLDB supports CHERI registers in core files; live debugging in-progress

Example object-capability/sandbox invocation: "hello world"



← Application main() invokes sandbox

← Sandbox invokes system-object puts()

← System object invokes libc puts()

← System-object puts() invokes libc puts()

← libc puts() invokes write() system call

← Kernel performs write()

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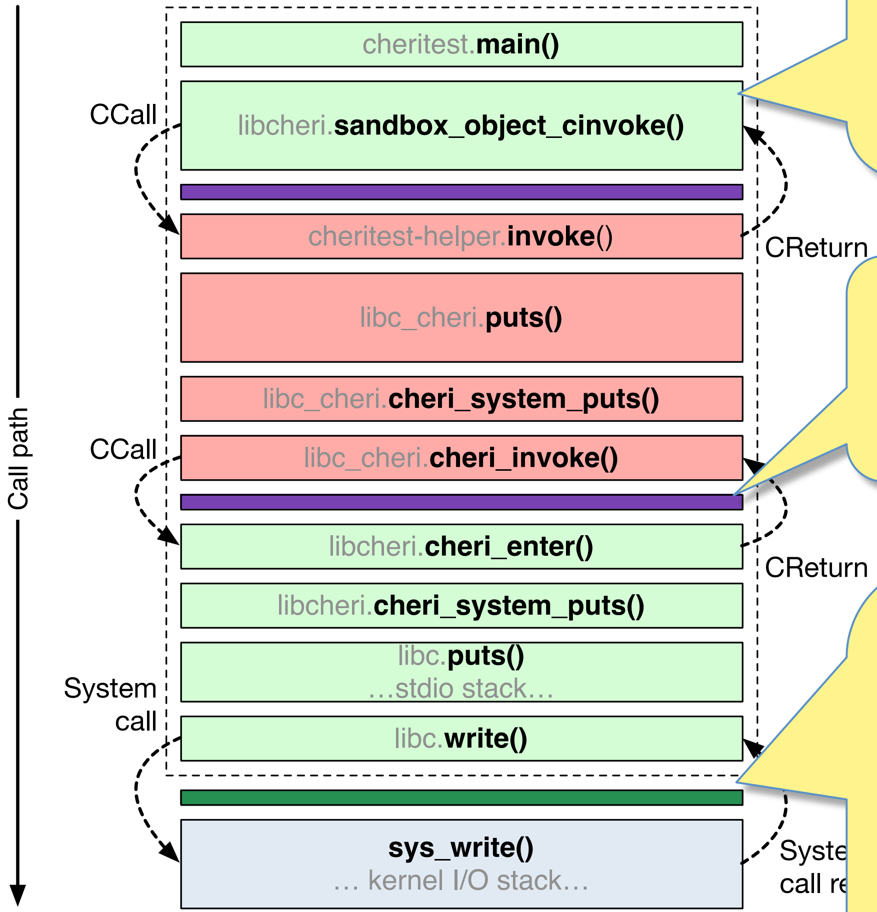
Example object-capability/sandbox invocation



← Sandbox invokes system-object puts()

Legacy MIPS code can appear throughout the stack, but requires access functions (i.e., copies) to access non-$c0 data

Rights passed between sandboxes must be described using capabilities

System-call interface remains largely unmodified: MIPS ISA/ABI

In the future, we will add hybrid CHERI-aware system calls allowed in sandboxes, but scoped by capability arguments

libcheri: object-capability sandbox API

- C-language bindings for CHERI object-capability sandboxes
- Sandbox class
  - For now, memory image; soon, ELF binary (or segment)
  - new, method_declare, destroy
  - Sandbox object
  - Instantiated class with data
  - new, getsystemobject, cinvoke, destroy
- Small assembly stubs for caller invoke() and callee enter()

```
LIBCHERI(3)              BSD Library Functions Manual              LIBCHERI(3)

NAME
     libcheri, sandbox_class_new, sandbox_class_method_declare,
     sandbox_class_destroy, sandbox_object_new,
     sandbox_object_getsystemobject, sandbox_object_cinvoke,
     sandbox_object_invoke, sandbox_object_destroy -- Library interface for
     CHERI sandboxing

LIBRARY
     library ``libcheri''

SYNOPSIS
     #include <machine/cheri.h>
     #include <machine/cheric.h>
     #include <sandbox.h>

     int
     sandbox_class_new(const char *path, size_t sandboxlen,
         struct sandbox_class **sbcpp);

     int
     sandbox_class_method_declare(struct sandbox_class *sbcp, u_int methodnum,
         const char *methodname);

     void
     sandbox_class_destroy(struct sandbox_class *sbcp);

     int
     sandbox_object_new(struct sandbox_class *sbcp,
         struct sandbox_object **sbopp);

     struct cheri_object
     sandbox_object_getsystemobject(struct sandbox_object *sbop);
     #if __has_feature(capabilities)

     register_t
     sandbox_object_cinvoke(struct sandbox_object *sbop, u_int methodnum,
         register_t a1, register_t a2, register_t a3, register_t a4,
         register_t a5, register_t a6, register_t a7, __capability void *c3,
         __capability void *c4, __capability void *c5, __capability void *c6,
         __capability void *c7, __capability void *c8, __capability void *c9,
         __capability void *c10);
     #else

     register_t
     sandbox_object_invoke(struct sandbox_object *sbop, u_int methodnum,
```

libc_cheri: sandboxed C library; libcheri system class

- Subset of key C functions
  - Useful functions useable without ambient authority (e.g., snprintf)
  - Bottom-end functions invoke CHERI system-class object capabilities instead of system calls
- Kernel rejects calls without ambient authority
  - Sandboxes must request operations with ambient effects through CHERI system class

procstat(1): sandbox monitoring

```
% slogin -i .ssh/id_cheri_host ctsrd@cheritest.sec.cl.cam.ac.uk
Last login: Sat Nov 16 03:26:50 2013 from ip-64-134-230-112.public.wayport.net
FreeBSD 11.0-CURRENT (CHERI_DE4_SDROOT) #8 825c7e7(master)-dirty: Sat Jan 11 00:35:25 GMT 2014

% procstat -RX 7114
 PID  COMM       CLASS                METHOD     INVOKE FAULT   SMIN    SMAX   SMEAN SMEDIAN
 7114 cheritest  cheritest-helper.bin md5             4     0  10116  158925   47478   10436
 7114 cheritest  cheritest-helper.bin abort           1     1   3187    3187    3187    3187
 7114 cheritest  cheritest-helper.bin helloworld      1     0 452296  452296  452296  452296
 7114 cheritest  cheritest-helper.bin puts            1     0 456118  456118  456118  456118
 7114 cheritest  cheritest-helper.bin syscall         1     0   6551    6551    6551    6551
 7114 cheritest  cheritest-helper.bin divzero         3     3   2900    3166    3005    2950
 7114 cheritest  cheritest-helper.bin malloc          0     0      0       0       0       0
```

- Libcheri exports statistics on sandbox classes, objects, and methods
- libprocstat(3) and procstat(1) can query/print this
- libprocstat(3) rovided data backend for demo UI

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In progress: open sourcing CHERI

- Complete open-source hardware-software research/teaching stack
- BERI Open Systems CIC ("Community Interest Company") Dec 2013
- BERI Apache-style license (HW), BSD license (SW)
- Physical designs for DE4 tablet, interconnect boards
- CHERI and CHERI2 Bluespec designs; debugging components/tools
- CHERI test suite, formal models
- FreeBSD device drivers
- CheriBSD capability support
- CHERI Clang/LLVM/LLDB
- ETA: January/February 2014

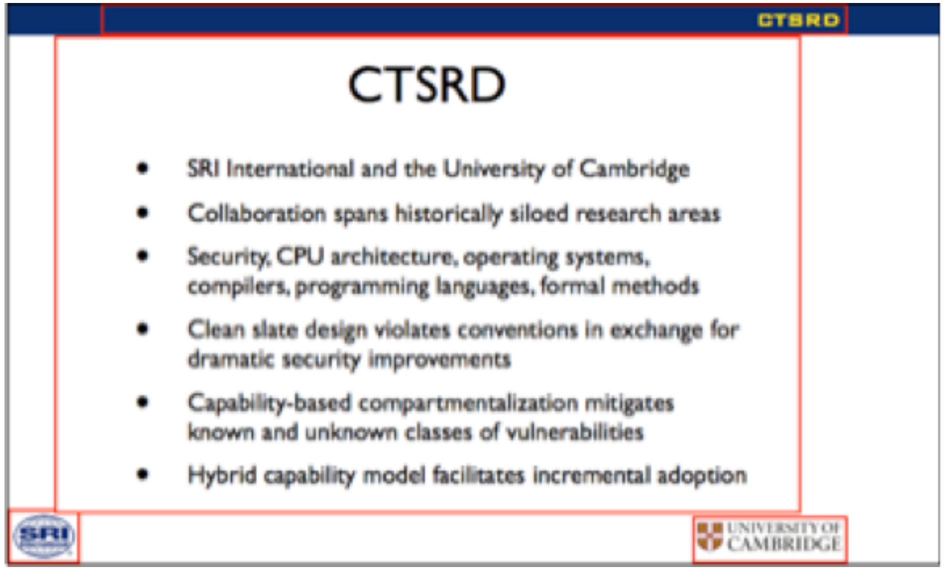
CHERI next steps

- CheriBSD kernel features (e.g., debugging, lazy switching)
- "Pure" CHERI ISA support for Clang/LLVM
- CHERI LLDB full feature support
- CCured-like automated use of memory protection
- Further CHERI ISA refinements: e.g., explicit CNULL
- Shift stack, heap access to CHERI ISA
- CCall/CReturn hardware optimizations
- Linker support for capabilities
- CHERI multithreading/multicore
- Additional languages: Object C, Ocaml

Compartmentalized packet capture and processing

CHERI DEMO

November 2012 - CheriPoint



- ✓ Bespoke compartmentalized CHERI presentation package
- ✓ Sandboxing mitigates trojan inserted in PNG library
- × Largely MIPS ISA code generated from C
- × A small amount of utility code written in CHERI assembly
- × Static sandboxing policy

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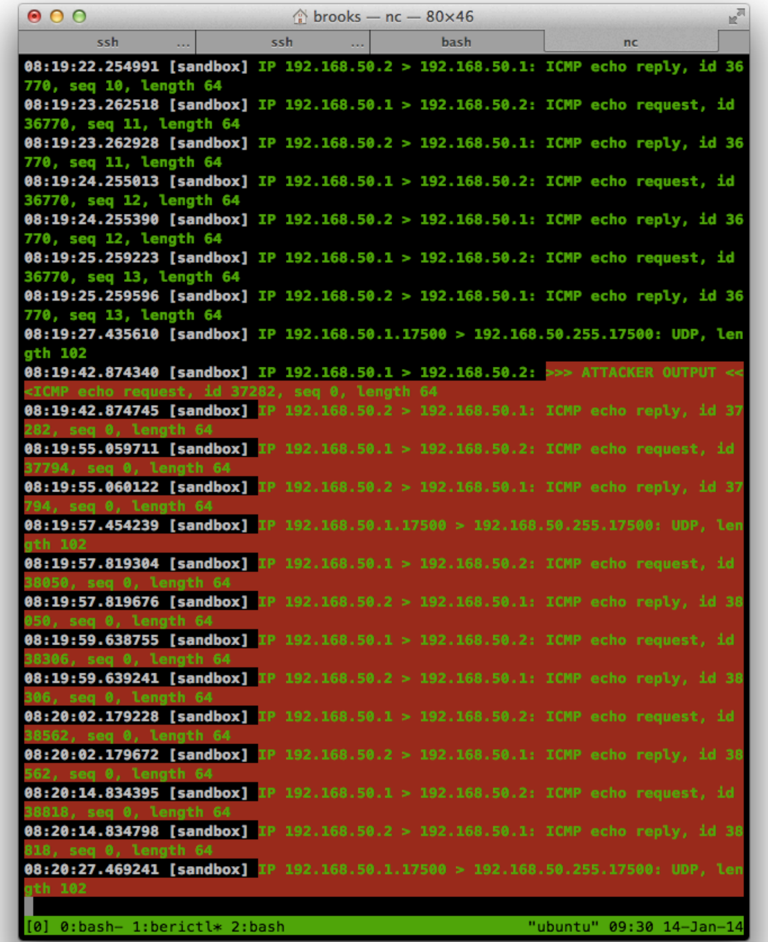
CHERI tcpdump demonstration

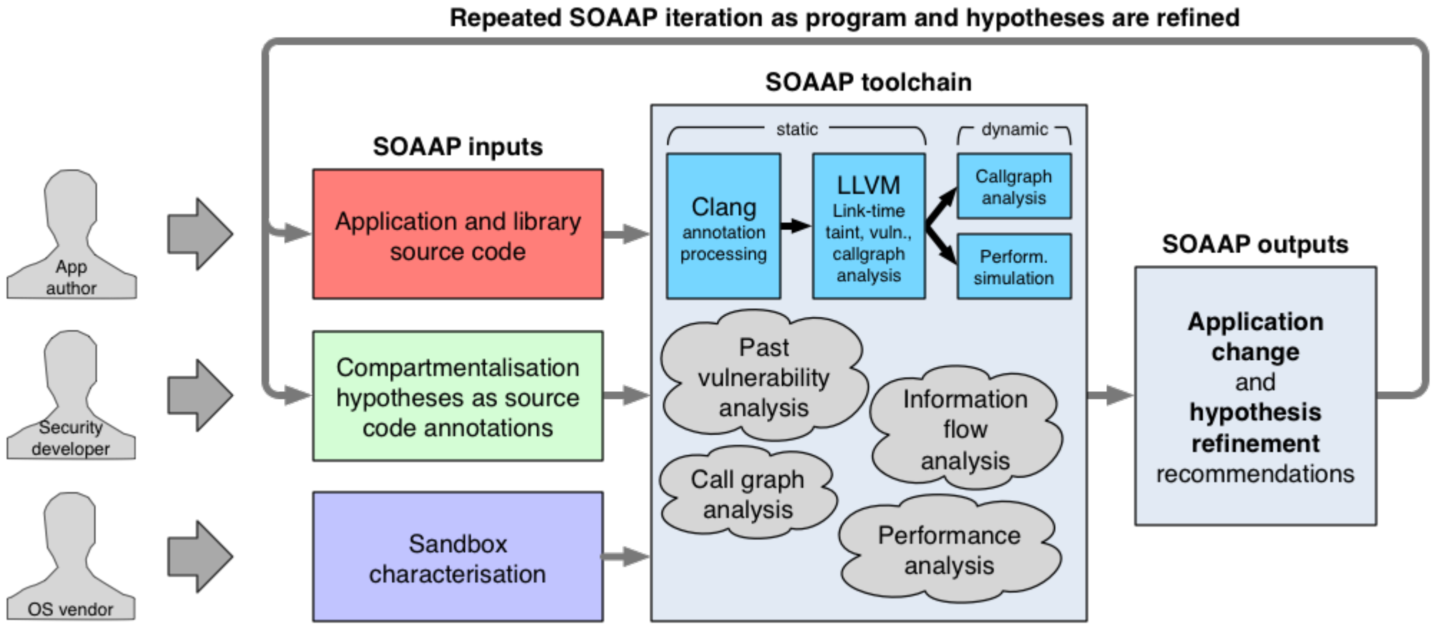
- Memory protection + compartmentalization
  - OS support for CHERI thread contexts
  - Compiler `__capability` pointers
  - Userspace libcheri sandboxing model
  - Compartmentalized packet printing
- Key results:
  - Applicability of hybrid capability model
  - Tight C-language/capability integration
  - Tradeoffs policy/performance/mitigation
  - Compartmentalization scalability
  - Variable granularity



Software analysis and transformation

SOAAP AND TESLA

Security-oriented analysis of application programs (SOAAP)

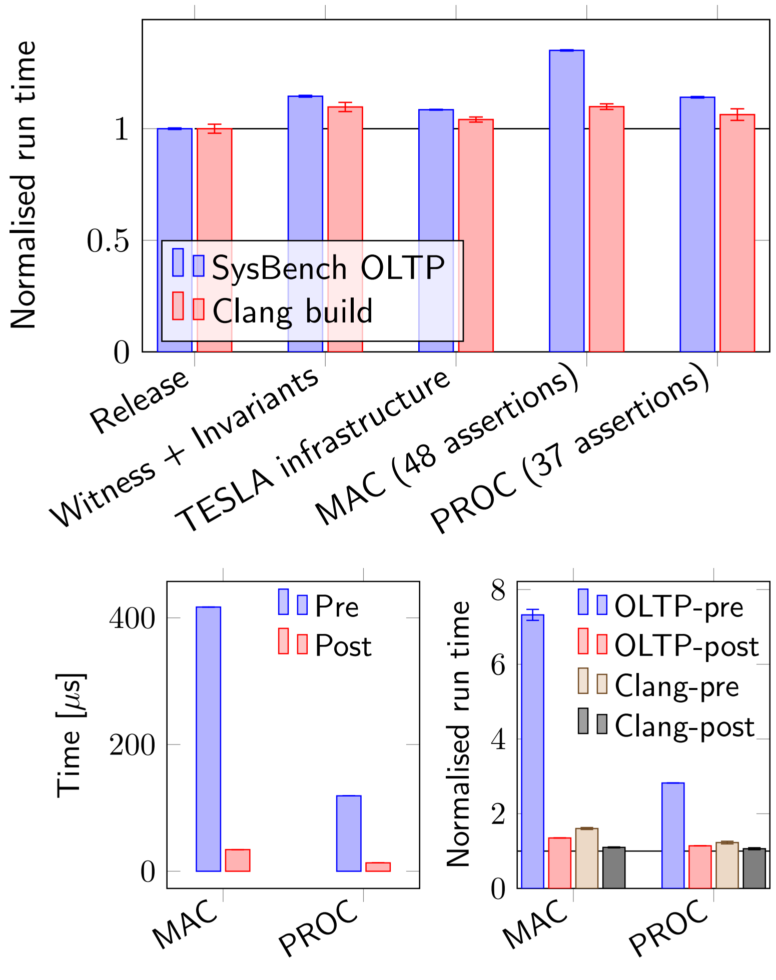


- Static and dynamic analysis tools to assist programmers when compartmentalizing applications
- Come see demo at poster session!

TESLA

- Pragmatic validation of run-time security properties
- LTL-like assertions embedded in code
- Compiler-generated instrumentation
- Significant outreach to potential open-source and corporate consumers
- Come see demo at poster session!

TESLA since last time



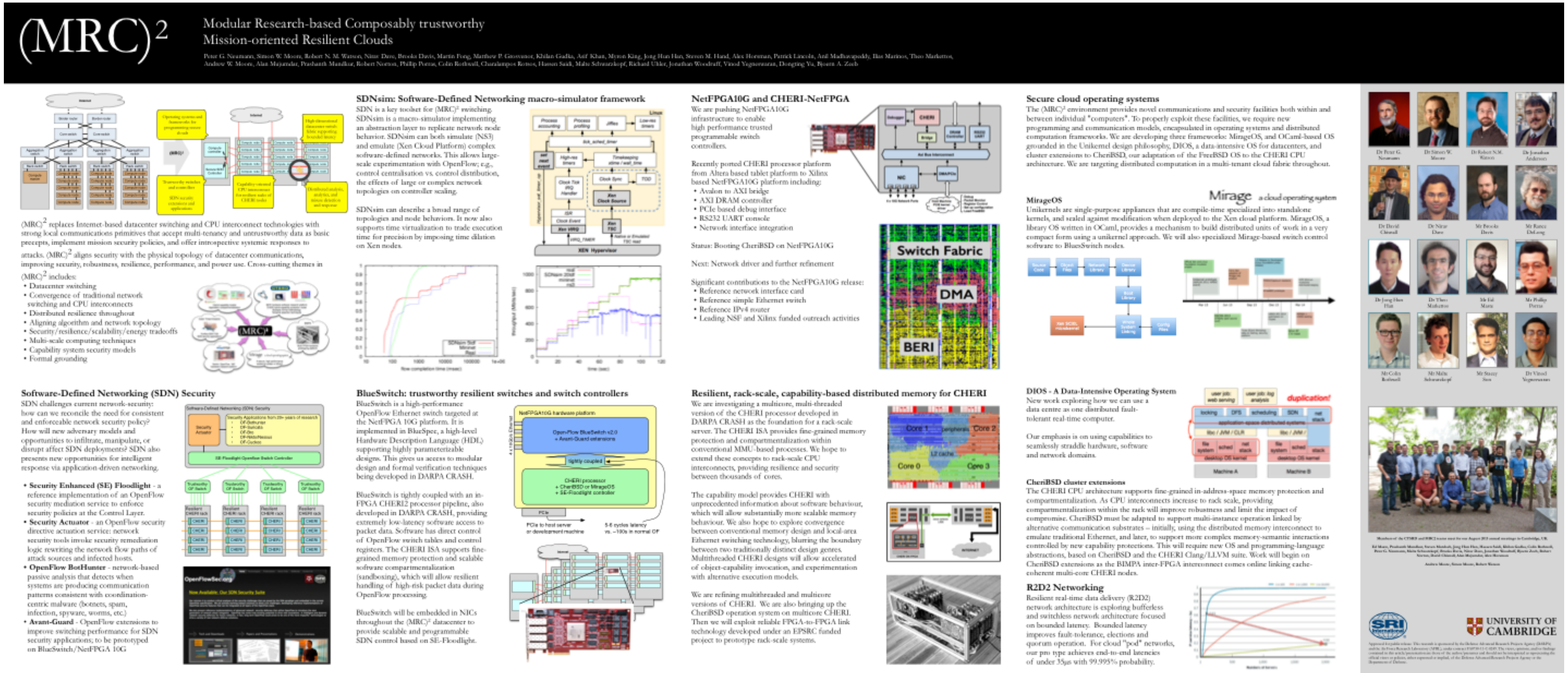
(a) Microbenchmark (b) Macrobenchmark

- Applied TESLA to OpenSSL, FreeBSD, Objective-C
- Found subtle bugs that eluded traditional debug tools
- Build cost: rebuilds less incremental
- Significant runtime cost optimizations

Conclusion

- Three years into the five-year project
- Mature CHERI hardware platform
- CheriBSD operating system
- CHERI Clang/LLVM/LLDB/SDK
- CHERI application exploration in progress
- SOAAP and TESLA tools maturing
- Smten, architectural extraction, and formal ISA models bearing early verification results

$(MRC)^2$ sister project



- Heavy use of CTSRD-derived CHERI
- Multithreaded and multicore CHERI prototypes
- CHERI on NetFPGA 10G

Q&A

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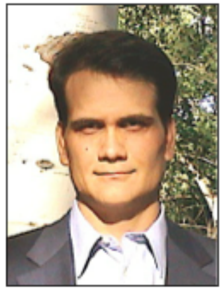
Mr Stacey Son